



# **Strengthening of Bridge Columns Subjected to an Impact Lateral Load Caused by Vehicle Collision**

## **Phase I Final Report**

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## **EXECUTIVE SUMMARY**

Fiber reinforced polymer (FRP) materials have gained wide acceptance for repair and retrofit of existing infrastructures or to design new infrastructures due to their desirable properties (high strength to weight ratio, light weight and consequent ease of field placement, corrosion resistance, durability, and low maintenance cost among others). There is a need to strengthen the deficient and aging civil infrastructure or new structures that are identified with certain design flaws against sudden loads including impact, blast, natural disasters, or increased traffic loads over time. The addition of FRP materials to upgrade the deficiencies or to strengthen the structural components prior to collapse can save lives and damage to infrastructure, and reduces the need for their costly replacement. The retrofit with the FRP materials with desirable properties provides an excellent replacement for traditional materials including steel jacket to strengthen the damaged reinforced concrete structural members that are repairable. Additionally, there are a number of accidental vehicle-bridge component collisions reported every year that result in loss of lives and severe property damages. These outcomes suggest that some of these bridges are not impact proof.

In this phase of the project, a literature review was performed on the FRP-strengthening of concrete bridge members and structural components to evaluate its use and benefits. In particular, the FRP strengthening of columns for several loading scenarios including impact load is discussed. Various forms of FRP strengthening techniques are also introduced. The existing studies have shown that the use of FRP materials restore or improve the member original design strength and in some cases allow the structure to carry an increased load that it was not designed for. It was also concluded that there is a need for additional research on the columns under impact load. The compiled information will help prepare the ground work for further evaluation of the bridges that are in serious need for repair or replacement either due to accidental impact or deterioration, and to propose an innovative and reliable bridge repair technique that is fast, durable and cost efficient.

## **INTRODUCTION**

Many bridges are in need of repair or replacement. Deficiency in bridges can be caused by design flaws, deterioration due to environmental impact, increase in service loads, and accidental impacts (Parvin and Brighton 2011).

Design flaws can occur when engineers improperly design a structure due to poor methods of analysis and lack of experience or when contractors fail to follow the plan and procedure outlined by the engineer. Pre-1970's buildings and bridges were constructed according to older design codes and need to be retrofitted to meet the current codes and standards. These structures can be subjected to higher live loads than they were originally designed for.

The environment can also play a devastating role on infrastructures. Natural disaster such as hurricanes, tornadoes, tsunamis, and earthquakes can damage or destroy structures in a matter of seconds. On the other hand, saltwater, deicing chemicals, and freeze-thaw cycles can cause deterioration over a longer period of time.

Every year, several overheight vehicles strike the bridge girders despite the regulations and practices set in place by governing bodies to restrict such occurrences from happening. Additionally, placement of barriers and guardrails does not always protect the bridge columns

from vehicular collision damage. The damage caused by such impacts can lead to concrete cover spalling or cracking, reinforcement damage or exposure, or in worst cases, structural failure. Fig. 1 shows damage caused by an overheight vehicle striking a bridge girder.

Natural disasters, vehicle collisions, and explosions have made engineers reevaluate current reinforced concrete structures for their effectiveness against resisting such loads. Previous retrofit techniques include concrete and steel jacketing. These methods are time consuming and labor intensive. They also increase the cross-sectional area of the member. In recent years, one method of repair that has become increasingly popular is the use of fiber reinforced polymers materials due to their excellent mechanical properties, high strength, corrosion resistance, durability, light weight, ease of application, reduced construction time, efficiency, and low life cycle cost (Ibrahim and Mahmood 2009; Stallings et al. 2000). The earliest type of FRP material used was glass fibers embedded in polymeric resins and appeared after World War II for space and air exploration (Bakis et al. 2002). Later on a variety of fiber materials were introduced to the market including aramid, boron, carbon, and Kevlar.



**Fig. 1.** Damage Caused by Overheight Vehicle Collision

The repair and strengthening of reinforced concrete structures can be done through the external reinforcement using FRP strips, sheets, and plates, or by near surface mounting (NSM), FRP spraying, and FRP prestressing. Brief description of various forms of FRP is provided in the following sections.

### **FRP Sheets and Strips**

FRP sheets and strips consist of wide or narrow fabrics, respectively, which are dipped into polymeric binder and then set into place. FRP strips are often used when FRP sheets are too

difficult to place or where only a minimal amount of FRP reinforcing is needed. FRP sheets and strips have been used to enhance the axial, shear, or flexural capacities of reinforced concrete members. Toutanji et al. (2010), Wu et al. (2009), and Matthys et al. (2006) investigated the axial capacity of FRP confined columns. Bouselham and Chaallal (2006), Ibrahim and Mahmood (2009), and Mosallam and Banerjee (2007) conducted research on improving the shear capacity of beams by FRP sheets and strips. Mayo et al. (1999) and Zhao et al. (2007) studied the flexural capacity and the bond of externally FRP-strengthened beams. Finally, Di Ludovico et al. (2010) employed external CFRP laminates to restore the loss in flexural capacity of damaged beams due to an impact load.

### **FRP Plates**

FRP plates consist of FRP fabric pre-impregnated with the binder material and allowed to cure before being attached to the desired member. FRP plates are often desired over FRP sheets or strips due to their rigidity for the ease of placement. Researchers including Stalling et al. (2000) and Nanni et al. (2004) have studied the retrofit of reinforced concrete beam members with shear or flexural deficiencies using FRP plates.

### **Near Surface Mounting**

Near Surface Mounting (NSM) consists of cutting a groove into the concrete surface. The groove is then filled half-way with an epoxy paste. The FRP rod is placed into the groove and the groove is then filled with more epoxy paste until the surface is leveled (Nanni et al. 2004). Investigations into the retrofit of reinforced concrete members with shear and flexural deficiencies using NSM include Nanni et al. (2004), Teng et al. (2006), Bianco et al. (2009), Nordin and Biorn (2006), and Hassan and Rizkalla (2003).

### **Sprayed FRP**

Sprayed FRP consists of a discontinuous fiber material encapsulated by a polymeric matrix resin. The biggest advantage for sprayed FRP is the simplicity of its application. The FRP is applied with a spray or chopper gun system. A better bond between the fiber and polymer is achieved since the matrix resin also acts as the bonding agent between the concrete and FRP. The epoxy used for this kind of application has lower viscosity which allows for better penetration into voids on the substrate surface (Boyd et al. 2008). Lee and Hausmann (2004), and Boyd et al. (2008) studied the retrofit of reinforced concrete members with shear and flexural deficiencies using sprayed FRP.

### **FRP Prestressing**

Prestressing of FRP sheets has many benefits including the effective use of tensile strength, active load-carrying mechanism, enhanced durability and serviceability, effective stress redistribution of existing reinforcement, and improved shear and flexural capacities of reinforced concrete members (Meier 1995; El-Hacha et al. 2001; Wight et al. 2001; Kim et al. 2005). The application of prestressed FRP can become more cumbersome due to the required anchoring system needed to maintain the prestressing in the FRP. Kim et al. (2005) investigated the

anchoring techniques of FRP prestressing. The effects of FRP prestressing on girders damaged by the impact load were also considered in another study by Kim et al. (2008). Meier (1995), El-Hacha et al. (2001), and Wight et al. (2001) investigated the strengthening of beams using FRP prestressing. Columns have been upgraded for lateral impact or seismic loads using prestressed FRP strips (Motavalli et al. 2011).

## **STRENGTHENING OF COLUMNS**

Columns can be strengthened to increase the axial, shear, and flexural capacities for a variety of reasons including: lack of confinement, eccentric loading, seismic loading, impact loading, and corrosion. In the following sections, these topics are discussed in further detail.

### **FRP Confinement of Columns**

Traditional methods to increase the load carrying capacity of columns include steel and concrete jacketing which lead to a much larger cross-sectional area for the column. FRP sheets or encasement can be used to increase the axial load carrying capacity of the column with minimal increase in the cross-sectional area. Confinement consists of wrapping the column with FRP sheets, prefabricated jacketing, or in situ cured sheets with fiber running in circumferential direction. The use of confinement increases the lateral pressure on the member which results in more ductility and higher load capacity. Confinement is less effective for rectangular than circular shape RC columns due to the confining stresses that are transmitted to the concrete at the four corners of the cross-section. The confinement effectiveness improves with the increase in the corner radius (Bakis et al. 2002). Recent studies (Wu et al. 2009; Matthys et al. 2006; Toutanji et al. 2010) show that FRP materials can be used to effectively increase the load carrying capacity of columns under axial loading. Examples of experimental data on the effect of FRP strengthening of axially loaded columns are shown in Table 1. The range of increase in axial load capacities of the columns varies from 6 to 176 %. The increase depends on several variables including the properties and the amount of FRP reinforcement, concrete strength, and axial load level.

**Table 1.** Representative Experimental Data on FRP-Axially Loaded Columns

Authors	Test ID	Retrofit	Increase in Load (%)	Failure Mode
Toutanji et al. 2010	K9	CFRP	14.89	FRP fracture
	K10	CFRP	8.51	FRP fracture
	K11	CFRP	6.38	FRP fracture
Wu et al. 2009	L-C-1	AFRP	68.55	FRP fracture
	L-C-2	AFRP	176.74	FRP fracture
	L-D-1	AFRP	2.02	FRP fracture
	L-D-2	AFRP	30.54	FRP fracture
	L-D-3	AFRP	61.21	FRP fracture
	M-C-1	AFRP	50.74	FRP fracture
	M-C-2	AFRP	112.80	FRP fracture
	M-C-3	AFRP	136.66	FRP fracture
	M-D-1	AFRP	6.76	FRP fracture
	M-D-2	AFRP	19.55	FRP fracture
	M-D-3	AFRP	29.44	FRP fracture
	H-C-1	AFRP	21.83	FRP fracture
	H-C-2	AFRP	52.15	FRP fracture
	H-C-3	AFRP	102.12	FRP fracture
	H-D-1	AFRP	-0.18	FRP fracture
H-D-2	AFRP	14.78	FRP fracture	
H-D-3	AFRP	9.98	FRP fracture	
Matthys et al. 2006	K2	CFRP	59.23	FRP fracture
	K3	CFRP	59.87	FRP fracture
	K4	GFRP	61.79	FRP fracture
	K5	GFRP	13.66	FRP fracture
	K8	CFRP/GFRP	32.98	FRP fracture

### Strengthening of Columns Subjected to Eccentric Axial Load

In field applications, most columns are not under perfect concentric loading. This produces a nonuniform confining stress due to the strain gradient which in turn reduces the effectiveness of the column (Parvin and Wang 2001). Traditional methods for the upgrade of eccentrically loaded columns include concrete and steel jacketing. These methods are successful in increasing the structural capacity of the column but are labor intensive, difficult to implement on site, and significantly increase the cross-section of the column. FRP retrofitting has none of the previous mentioned problems. Recently, research has been conducted on the eccentric axial loaded column retrofitted with FRP sheets. Parvin and Wang 2001 studied the effects of the jacket thickness and various eccentricities on the CFRP-retrofitted columns. Maaddawy (2009) examined the effect of eccentricity to section height ratio on the confinement of axially loaded columns. Yi et al. (2006) conducted experiments on FRP-retrofitted columns with various fiber orientations. Li and Hadi (2003) and Hadi (2006) evaluated the effectiveness of CFRP and GFRP sheets on high strength and normal strength concrete, respectively. Hadi (2007) compared the effectiveness of CFRP and GFRP retrofitted columns to steel jacketed columns. Examples of data obtained in research conducted on eccentrically loaded columns are shown in Table 2. Again, the FRP retrofit clearly enhanced the capacity of eccentrically loaded columns as compared to as-built columns.

**Table 2.** Representative Data on Eccentrically Loaded Columns

Authors	Test	Retrofit	Eccentricity (mm)	Increase in load (%)
Hadi 2007	G0	GFRP	50	11.94
	G1	GFRP	50	38.82
	G3	GFRP	50	57.84
	C0	CFRP	50	55.11
	C1	CFRP	50	109.42
	C3	CFRP	50	124.64
Hadi 2006	C2	CFRP	42.5	7.35
	C3	CFRP	42.5	4.99
	C4	CFRP	42.5	-1.84
	C6	CFRP	42.5	22.57
Parvin and Wang 2001	C11	CFRP	7.6	44.40
	C21	CFRP	7.6	79.00
	C12	CFRP	15.2	47.87
	C22	CFRP	15.2	80.98
Maaddawy 2009	FW-e1	CFRP	37.5	37.21
	FW-e2	CFRP	54	24.24
	FW-e3	CFRP	71	8.28
	FW-e4	CFRP	107.5	3.26
	PW-e1	CFRP	37.5	27.91
	PW-e2	CFRP	54	21.21
	PW-e3	CFRP	71	3.45
	PW-e4	CFRP	107.5	1.09
Yi et al. 2006	C10L-1	CFRP	175	5.00
	C01L-1	CFRP	175	6.70
	C01S-1	CFRP	35	7.70
	C02S-1	CFRP	35	13.30
	C10L-3	CFRP	175	13.40
	C01L-3	CFRP	175	4.60
	C20L-3	CFRP	175	22.00
	C11L-3	CFRP	175	21.00

### Strengthening of Columns Subjected to Impact Loads

With consistently increasing traffic in recent years, vehicular collisions with bridge columns have become more of a prevalent issue (Parvin and Kulikowski 2011). Vehicles often strike columns or piers despite the measures put in place such as guardrails and barriers. Such impacts can lead to concrete spalling or cracking, reinforcement damage or exposure, girder misalignment, connection failure or in worst cases structure failure (Boyd et al. 2008). Most column designs account for static loading only, while an impact load due to a vehicle collision is highly dynamic. There are certainly many existing bridges that could be deficiently designed in the case of vehicular impact. Several studies have been conducted concerning the dynamic effects of a high impact vehicle collision with bridge piers and columns (El-Tawil et al 2005; Ferrier and Hamelin 2005; Tsang and Lam 2008; Thilakarathna et al 2010). FRP retrofit can offer a quick and

economical repair as compared to traditional methods. However, studies looking into the FRP retrofit of columns for impact loads are extremely limited. Ferrier and Hamelin (2005) performed experimental investigation on as-built and CFRP-strengthened RC beams and columns. The specimens were subjected to static and dynamic impact loads. For the static load tests that were conducted on three RC beams, the ultimate load of the CFRP-strengthened specimen was 62 % higher than the as-built specimen. In the dynamic test, it was observed that the CFRP-strengthened RC column load capacity was 88% higher than an as-built specimen. Through both static and dynamic tests, it was found that the use of CFRP material significantly increased the strength of RC columns under impact loading.

### **Strengthening of Columns Subjected to Seismic Loads**

Reinforced concrete structures built prior to the modern day design codes may have been insufficiently designed to survive a severe earthquake. Numerous studies involve the FRP retrofit of reinforced concrete columns for seismic loads. Gu et al. (2010) investigated the effects of the FRP reinforcement length on the plastic hinge region and the drift capacity of FRP-retrofitted columns. Lacobucci et al. (2003) examined the increase in the ductility and energy dissipation capacities of FRP-retrofitted reinforced concrete columns. Wu et al. (2008) studied a new method of retrofitting square or rectangular reinforced concrete columns by embedding reinforcement bars into the plastic hinge zone to increase the ductility of the concrete in this region.

### **Strengthening of Columns Subjected to Corrosion**

Reinforced concrete columns are susceptible to corrosion from marine environments, fire, and deicing agents. FRP retrofitting of a reinforced concrete column involves jacketing the column with the FRP material and filling the voids between the jacket and the concrete surface with conventional or expansive grout (Pantazopoulou et al. 2001). In their study the different types of diffusion barriers to protect GFRP-retrofitted columns were investigated. Tastani and Pantazopoulou (2004) examined the jacket characteristics and the repair method. Bae and Belarbi (2009) studied the effectiveness of CFRP sheet in protecting the RC columns from corrosion of the steel reinforcement. The research has shown that FRP retrofit was a practical alternative to conventional methods due to its superior performance in enhancing the strength and ductility of RC columns. Performance was markedly improved by increasing the number of FRP layers and by providing sufficient anchorage for each layer (Pantazopoulou et al. 2001; Tastani and Pantazopoulou 2004). FRP are very efficient as repair materials which can also decrease the rate of corrosion (Tastani and Pantazopoulou 2004; Bae and Belarbi 2009).

### **Field Application Projects Related to FRP Repaired Columns**

Recent field application projects for strengthening of structure and bridge columns with FRP are shown in Tables 3, 4 and 5. The types of repairs include: corrosion, confinement, axial, flexural, shear, and seismic strengthening. In the state of California external FRP retrofit is commonly done due to the need for seismic strengthening.

**Table 3. Selected Field Application Projects - Columns Retrofitted for Axial Loads or Confinement**

Agency	Structure	Date	Location	Type of Repair	Material
Quakewrap	Port Clinton Garage	2009	Port Clinton, OH	Axial	GFRP
FYFE Co. LLC	Corona Del Mar	2009	Orange Co. CA	Confinement	GFRP
D.S. BROWN	Medford Fire Station	2007	Medford, OR	Axial	CFRP
D.S. BROWN	Los Gatos Creek Bridge	2007	Santa Clara, CA	Axial	CFRP
Quakewrap	Cabana Hotel	2007	Miami Beach, FL	Axial	CFRP
Quakewrap	Rocky Mountain Hardware	2007	Hailey, ID	Axial	CFRP
D.S. BROWN	House Seismic	2005	Puako, HI	Axial	CFRP
D.S. BROWN	Childrens Hospital	2005	Seattle, WA	Axial	CFRP
D.S. BROWN	PNC Bank	2004	Lexington, KY	Axial	CFRP
D.S. BROWN	I-10 Overcrossing	2003	Los Angeles, CA	Axial	CFRP
Quakewrap	Plaza In Clayton	2003	St. Louis, MO	Axial	CFRP
D.S. BROWN	Dolphin Condos	2002	Malibu, CA	Axial	CFRP
D.S. BROWN	First Union Bldg	2002	Charlotte, NC	Axial	CFRP
D.S. BROWN	Precast Concrete Plant	2001	Boise, ID	Axial	CFRP
FHWA 2007	US 64 WB over Haw River	2000	North Carolina	Confinement	GFRP
FHWA 2007	Androscoggin River Bridge	1999	Mexico, Maine	Confinement	FRP
FHWA 2007	East Street Viaduct over WV Alt 14A	1999	West Virginia	Confinement	CFRP
FHWA 2007	I-96 over US 27	1999	Lansing, MI	Confinement	CFRP/GFRP
FHWA 2007	I-80 at State Street	1999	Utah	Confinement	FRP
Quakewrap	Phoenician Resort	1999	Scottsdale, AZ	Confinement	CFRP
FYFE Co. LLC	Harris Hospital Parking Garage	1994	Fort Worth, TX	Axial	GFRP

**Table 4. Selected Field Application Projects - Columns Retrofitted for Corrosion**

Agency	Structure	Date	Location	Type of Repair	Material
FYFE Co. LLC	Chula Vista Bayside Park Pier	2009	San Diego, CA	Corrosion	CFRP & GFRP
Quakewrap	Bay View Bridge	2007	Ft. Lauderdale, FL	Corrosion	CFRP
Quakewrap	I-90 Bridge at Cline Ave.	2006	Gary, IN	Corrosion	GFRP
Quakewrap	I-94 Bridge at S.R. 49	2006	Chesterton, IN	Corrosion	GFRP
Quakewrap	Tucson Main Library	2005	Tucson, AZ	Corrosion	GFRP
D.S. BROWN	Bahia Honda Bridge	2003	Florida Keys	Corrosion	CFRP
FYFE Co. LLC	Miramar Water Treatment Plant Clearwell 2	2003	San Diego, CA	Corrosion	FRP
FYFE Co. LLC	Malibu Residence	2001	Malibu, CA	Corrosion	FRP
Quakewrap	I-40 Bridge	1997	Oklahoma City, OK	Corrosion	GFRP

**Table 5. Selected Field Application Projects - Columns Retrofitted for Seismic Loads**

Agency	Structure	Date	Location	Type of Repair	Material
D.S. BROWN	Day's Inn	2008	Portland, OR	Seismic	CFRP
Quakewrap	Ted Stevens International Airport	2008	Anchorage, AK	Seismic	CFRP
FYFE Co. LLC	Pasadena City Hall	2007	Pasadena, Ca	Seismic	FRP
FYFE Co. LLC	2025 South Figueroa	2007	Los Angeles, CA	Seismic	GFRP
D.S. BROWN	Vista House	2005	Portland, OR	Seismic	GFRP
Quakewrap	McKinley Tower	2005	Anchorage, AK	Seismic	CFRP & GFRP
D.S. BROWN	Mountainview Overcrossing	2004	Reno, NV	Seismic, Flexural & Shear	CFRP
D.S. BROWN	Mogul East & Mogul West	2004	Mogul, NV	Seismic/Shear	CFRP
D.S. BROWN	Glendale Parking	2002	Glendale, CA	Seismic	CFRP
FYFE Co. LLC	Sobrante WTP Clearwell Roof	2002	El Sobrante, Ca	Seismic	GFRP
FYFE Co. LLC	L.A. Sports Arena	2002	Los Angeles, CA	Seismic	GFRP
D.S. BROWN	Richmond Police HQ	2001	Richmond, CA	Seismic	CFRP
FYFE Co. LLC	Big Tujunga Canyon Bridge	2001	Los Angeles, CA	Seismic	FRP
FYFE Co. LLC	Arroyo Quemado Bridge	1999	Santa Barbara, CA	Seismic	FRP

## CONCLUSIONS

This report has provided a review of recent experimental research and field application projects on the FRP retrofit of reinforced concrete structures. The existing studies have shown that the use of FRP materials restore or improve the member original design strength and in some cases allow the structure to carry an increased load that it was not designed for. With more field application projects, FRP will continue to grow in popularity as a retrofit material over traditional materials due to its superior material properties such as lightweight, resistant to corrosion, and ease of application which results in shortening the construction time.

From the review of the literature, it was also concluded there is a need to perform additional research on the FRP retrofit of concrete members subjected to impact loadings. With further investigations, life cycle costs will outweigh the higher upfront cost of FRP retrofit over conventional retrofit techniques.

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